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The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas

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Abstract

Among the many benefits of solar photovoltaic (PV) systems, the direct effects are those of providing local power and the indirect ones include avoided generation from fossil-fuel power plants. The latter translate into reduced emissions of greenhouse gas (thus reduced radiative forcing) and other pollutants, such as ozone precursors (thus improved air quality). Because large-scale PV deployments can alter the radiative balance at the surface-atmosphere interface, they can exert certain impacts on the temperature and flow fields.

In this analysis, meteorological modeling was performed for the Los Angeles region as a case study to evaluate the potential atmospheric effects of solar PV deployment. The simulations show no adverse impacts on air temperature and urban heat islands from large-scale PV deployment. For the range of solar conversion efficiencies currently available or expected to become attainable in the near future, the deployment of solar PV can cool the urban environment. The cooling can reach up to 0.2 C in the Los Angeles region. Under hypothetical future-year scenarios of cool cities (urban areas with extensive implementations of highly-reflective roofs and pavements) and high-density deployments of urban solar PV arrays, some adverse impacts (0.1 C or less in warming) might occur. However, such extreme high-density deployments of cool surfaces are not expected and thus the warming effects are unlikely to result.
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1. Introduction

An ambitious portfolio of renewable energy measures in California calls for a variety of technologies to be implemented both on the short and long terms. For solar generation, Governor Brown's *Clean Energy Jobs Plan* (CEC, 2011) suggests that solar systems of up to 2 MW be installed on the roofs of warehouses, parking lot structures, schools, and other commercial buildings throughout the state, and that solar energy projects of up to 20 MW in size would be built on public and private property. The State would also create the *California Solar Highway* by placing solar panels along the banks of highways and freeways. This is not counting voluntary installations of solar systems by developers or home and business owners.

Such large-scale deployments of solar PV arrays can have several impacts. The direct effect is the benefit of generating electricity whereas the indirect effect includes (1) the impact on the ambient environment and (2) avoided emissions from fossil-fuel power plants. Depending on the configuration of the solar arrays (envelope-embedded or detached/elevated), additional direct effects can also be accounted for, e.g., shading of the underlying roof structures or parking lots. Depending on the thermal integrity of the roofs and the configurations of parking lots, these effects may or may not be significant. Solar power generation contributes to air quality improvements and greenhouse-gas emission curtailments by avoiding fossil-fuel power-plant electricity generation.

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The goal of the study summarized in this paper is to evaluate and quantify the potential *indirect* impacts on the atmosphere of large-scale solar PV deployment focusing on changes in air temperature. The region-wide impacts are assessed via atmospheric mesoscale and meso-urban (fine-resolution) modeling, using the Los Angeles region as a case study. The purpose is to evaluate the benefits (e.g., reduction in air temperature) or possible negative effects, e.g., impacts on the urban heat island. In this paper, we do not present the beneficial direct effects of solar systems, i.e., the power they generate or their effects on heat flow through building envelopes. Several tools, such as the Department of Energy's Roof Calculator (DOE, 2012) or the calculator developed by NREL (2012), can be used to evaluate those tradeoffs and impacts on energy use in buildings. We also do not examine the effects of utility-scale solar power plants, e.g., such as those in the desert (Millstein and Menon, 2011).

2. Meteorological models and surface characterization

This study uses mesoscale and meso-urban meteorological models to evaluate the potential atmospheric impacts of solar PV deployment. These models and their applications are discussed in detail elsewhere. Only a brief summary is given here.

The PSU/NCAR MM5 (v3–7-4) mesoscale meteorological model is described in Dudhia (1993) and Grell et al. (1991,1994). For simulating the potential impacts of urban heat islands and their mitigation, a modified version of the MM5 was extensively used by Taha (2005,2007). In this study, we also used a version of the urbanized MM5 (uMM5) discussed in Taha (2008a,b) for fine-resolution (sub-kilometer) simulations. The model is based on the DA-SM2-U modifications of DuPont et al. (2004). Recent applications of the uMM5 (Taha, 2007,2008a-c) include heat island modeling studies, photochemical and air-quality modeling, and studies of urban-induced precipitation. In terms of data needs, the uMM5 requires special input beyond that of the standard MM5 (e.g., meteorological initial and boundary conditions, 4-dimensional analyses, surface characterization) consisting of detailed 3-dimensional fine-resolution morphological and geometrical parameters input. For a full discussion, refer to Taha (2007, 2008a,b). Performance evaluation for meteorological models used here has been established, thoroughly tested, and discussed in detail in Taha (2007, 2008a–c).

Unlike a mesoscale model that treats the surface as flat, the modified formulation of the uMM5 allows it to capture the effects of installing solar PV on different types of roofs, at different heights, and in different 3-dimensional geometrical configurations. The fine horizontal and vertical resolutions of the model also facilitate capturing the effects of solar PV on air temperature at various elevations within the urban canopy layer. However, no distinction was made at this scale between envelope-integrated (flush) PV panels and elevated ones. This would have required much finer resolution modeling, e.g., CFD, or panel-scale energy balance calculations (e.g., Genchi et al. (2003)) which was beyond the scope of this study. Meso-urban-CFD coupled simulations are planned for future research efforts.

Surface characterization in the model is done based on fine-resolution (200-m) analysis of land-use/land-cover (LULC) and urban morphology data (Burian et al., 2003). All thermo-physical properties, e.g., albedo, soil moisture, roughness length, thermal inertia, frontal-, top-, and plan-area densities, building heights, wall-to-plan ratios for buildings and vegetation, and other relevant parameters, are characterized at 200-m resolution. The approach is described in Taha (2008b). Fig. 1a, shows the computed base-case albedo (averaged at 5 km) for present-day conditions in the Los Angeles region, without solar PV deployment.

3. Technical potential

The technical potential (deployability) of solar PV arrays in urban settings depends on several factors, including land-use/land-cover (LULC) characteristics, surface area available for solar installations, solar resources, and access.

The deployability of solar PV arrays in urban areas has been developed via several approaches. For example, Chaves and Bahill (2010) computed the technical potential using a digital elevation model based on LiDAR data. Navigant (2007) used a market-based penetration model to calculate the technical potential for solar PV in urban areas in California. Taha (2007) developed technical potential based on the USGS Level-II LULC classification system (Anderson et al., 2001). Using this approach for the Los Angeles region and for conditions representing the past 5–10 years, we estimate here a total technical potential of between 71 and 137 km^2, which is comparable to the market-based estimates developed by Navigant (2007). The total urban area in the Los Angeles region is 5400 km^2 (the total area of all 200-m cells that are classified as urban in the USGS Level-II classification system).

In this paper, we focus on solar PV deployment potentials for *roofs*. For each of the present-year and hypothetical future-year cool-cities conditions, two PV deployment scenarios are evaluated as shown in Table 1.

The technical potential in each 200-m LULC analysis cell is then computed from the product of roof fraction (column 2) and one of the deployment levels (columns 3 or 4). Deployment levels lower than those shown in column 3 were modeled in this study but found to have no detectable impacts on the atmosphere and are thus not discussed in this paper. Column 4 can also represent a scenario where in addition to roofs, PV arrays are deployed on parking lots or highway banks. Fig. 1b and c shows computed solar PV deployability (fraction of 200-m cells) for the Los Angeles region corresponding to the scenarios in columns 3 and 4, respectively.

4. Effective albedo of solar PV panels

For atmospheric modeling purposes, e.g., for evaluating the impact on ambient air temperature, the effective absorptivity of solar PV panels can be defined as:

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